ELSEVIER
Available online at www.sciencedirect.com
ScienceDirect
Procedia Engineering 5 (2010) 862–865
Procedia Engineering
www.elsevier.com/locate/procedia

Proc. Eurosensors XXIV, September 5-8, 2010, Linz, Austria

PVDF and EMFi sensor materials – A comparative study

Satu Rajala*, Jukka Lekkala

Department of Automation Science and Engineering, Tampere University of Technology, P.O. Box 692, FI-33101 Tampere, Finland

Abstract

This study compares the force sensing properties of polyvinylidenefluoride (PVDF) and ElectroMechanical Film (EMFi) sensor materials. The PVDF material has solid structure whereas the structure of the EMFi material is cellular. Due to the structural differences, some of the material properties differ. The sensor operation is evaluated here with force sensitivity measurements. The sensitivity is measured in directions related to the length, width and thickness of the sensor. The EMFi material is sensitive to dynamic forces exerted normal to its surface, and the sensitivity in that direction ((58.7 ± 16.5) mV/N) was found to be about five-fold when compared to the corresponding value of the PVDF material ((12.6 ± 0.8) mV/N). The PVDF material also detects the forces related to its length and width while the EMFi material has very low sensitivity to these force components.

Keywords: sensor material; PVDF; EMFi; sensitivity; normal force; shear force

1. Introduction

Piezoelectricity has been widely investigated in a number of polar polymers, such as ferroelectric polyvinylidenefluoride (PVDF) [1]. A classical definition of piezoelectricity is the change of electrical polarization in a material in response to mechanical stress [2].

The studied films have usually been homogenous and solid in structure. The properties of these materials are related to the intrinsically anisotropic molecular structure [3]. Instead, cellular polymers mimic piezoelectricity by their unusual electromechanical properties [4]. The piezoelectricity is not caused by symmetry breaking on the molecular or unit cell level, but on a macroscopic level [5]. The charge signal is related to the voided structure of cellular electrets and not to the piezoelectricity of the base material. ElectroMechanical Film (EMFi) invented in Finland in 1987 is the first truly cellular polymer electret film available for commercial applications [3].

This study aims to compare the properties of the PVDF and EMFi materials. The sensor operation is evaluated with sensitivity measurements and the preliminary results are reported. The structure of the paper is as follows. Section 2 briefly introduces the sensor materials used in this study. Section 3 describes the sensitivity measurement setup. In Sections 4 and 5 the results obtained are reported and discussed, respectively.

* Corresponding author (née Kärki). Tel.: +358-40-8490941; fax: +358-3-3115 2171.
E-mail address: satu.rajala@tut.fi.

doi:10.1016/j.proeng.2010.09.245

2. Sensor materials

2.1. Polyvinylidenefluoride (PVDF)

PVDF is a semicrystalline polymer having a solid and homogenous structure with approximately 50-65 % crystallinity [6]. The morphology of the polymer consists of ordered regions of monomer units dispersed within amorphous regions [2].

The manufacturing process of the PVDF material is described e.g. in references [6] and [7]. Briefly, the PVDF sheet is stretched at the temperature close to the melting point to cause a chain packaging of the molecules into piezoelectric β crystalline phase. These dipole moments are randomly oriented and result in a zero net polarization. In the polarization stage, the stretched polymer is exposed to a high electric field to generate piezoelectric properties. The molecular dipoles are oriented in the direction of the field and a net polarization is formed. Finally, to provide electrodes, the film is metalized.

If an external force compresses the film, the dipole orientation is changed and an electrical signal is induced on the electrodes [3]. The PVDF is anisotropic material and thus its electrical and mechanical properties differ depending on the direction of the external force. The piezoelectric coefficients, d_{ij} and g_{ij}, charge and voltage respectively, possess two subscripts; the coefficients are related to the electric field produced by a mechanical stress. The first subscript refers to the electrical axis and the second to the mechanical axis [7].

The three major axes (x, y and z) of piezoelectric materials are referred to as 1, 2 and 3, and the shear about these axes is represented by 4, 5 and 6, respectively. The axis 1 refers to the stretching direction, the axis 2 to the transverse planar direction and the axis 3 to the poling axis which is perpendicular to the material surface. Since the electrodes are on the top and at the bottom of the film, the electrical axis is always 3; the mechanical axis n can be 1, 2 or 3 since the stress can be applied to any of these axes [7].

The output voltage V_O of a PVDF sensor is defined as:

$$V_O = g_{3n} X_n t$$

where g_{3n} is the piezoelectric coefficient, X_n is the applied stress and t is the film thickness [7].

Table 1 lists the typical properties of a 28 μm thick PVDF material. The film with silver ink metallization used in this study was manufactured by Measurement Specialties Inc. (Hampton, USA).

2.2. ElectroMechanical Film (EMFi)

EMFi is a thin polypropylene (PP) material having a special cellular structure. The internal structure of EMFi is made be stretching the PP preform during the manufacturing process in longitudinal and transversal directions [8]. The film is charged with a corona discharge method using electric field strength locally exceeding the film dielectric strength [9]. Finally, the film is coated with electrically conductive electrode layers.

The EMFi material consists of three layers: smooth and homogenous surface layers and a dominant, thicker midsection [10]. The midsection is full of flat gas voids separated by leaf-like PP-layers. The voids can be compared to large electrical dipoles that are easily compressed in thickness direction by externally applied pressure [3].

The EMFi material is sensitive to dynamic forces exerted normal to its surface [11]. With cellular polymers, large values up to several hundreds pC/N are achieved for d_{33}, while the d_{31} and d_{32} coefficients are only of the order of one pC/N [5]. The change in thickness modifies the macro dipoles and generates a corresponding charge and hence, a voltage to appear at the electrodes. The output voltage ΔV of an EMFi sensor can be calculated as [12]:

$$\Delta V = (1/C) \cdot S \cdot \Delta F$$

where ΔF is the impact force, C is the capacitance and $S = d_{33}$ the sensitivity coefficient of the sensor.

Table 1 shows some characteristics of an EMFi film. The material is commercially available through a Finnish company Emfit Ltd (Vaajakoski, Finland). The material used in this study was 70 μm thick with aluminium electrodes.

Table 1. Typical properties of 28 μm thick PVDF [7] and 70 μm thick EMFi [3] materials.

Property	Symbol	PVDF 28 μm	EMFi 70 μm	Unit
Piezoelectric coefficient	d_{33}	-33	170	pC/N
	d_{31}	23	2	pC/N
Young's modulus	Y	$2{\cdot}10^9$ - $4{\cdot}10^9$	$< 1{\cdot}10^6$	N/m^2
Pyroelectric coefficient	p	30	0.25 - 045	μC/m^{2}K
Capacitance	C	380	14	pF/cm^2
Permittivity	ε	106 - 113	10	pF/m
Mass density	ρ	$1.78{\cdot}10^3$	330	kg/m^3
Dynamic range	p	$1{\cdot}10^{-6}$ - $5{\cdot}10^9$	$< 1{\cdot}10^6$	Pa

3. Sensitivity measurements

Four identical PVDF and EMFi sensor elements (size 3 cm x 3 cm) were constructed from commercial film materials for the sensitivity measurements. The charge flow of each sensor element was measured with a charge amplifier circuit (AD711 by Analog Devices).

The operation of the PVDF and EMFi sensor elements was evaluated with sensitivity measurements [13]. The sensor elements were calibrated for each force components (mechanical axis n = 1, 2, 3) separately. The Brüel & Kjaer Mini-Shaker Type 4810 was used in the calibration to generate a dynamic excitation force. A commercial high sensitivity dynamic force sensor (PCB Piezotronics, model number 209C02) was used as a reference sensor for the dynamic excitation force. A load cell (Measurement Specialties Inc., model number ELFS-T3E-20L) was used as reference sensor to measure the static force between the sample and shaker's piston. A pretension, which is producing static force, is needed to keep the sample in place and to prevent the piston jumping off the surface during the measurement. Sensitivity of a sample is an average of six measurements.

The measurement setups for the normal force and the shear force components are shown in Fig. 1. To measure the normal force sensitivity (n = 3) of the sensor element, the sensor was placed horizontally on the metal plate. A static force of 3 N was adjusted between the sensor element and the shaker's piston with a position adjustment knob. The sensor was excited with dynamic sinusoidal force with the amplitude of 1.5 N and frequency of 1 Hz. The output voltage provided by the sensor element was measured. The force sensitivity was obtained by dividing the output voltage of the sensor element with the force measured by using the reference dynamic force sensor. The unit of sensitivity is thus V/N.

To measure the shear force sensitivities (n = 1 and n = 2), the sensor element was attached in a vertical position to generate a shear force. The sensor element was taped between a support block and a plastic board. The dynamic excitation force was exerted on the plastic board to stretch the sensor in the directions of mechanical axes n = 1 and n = 2. A smaller dynamic excitation force of 0.15 N was used due to the smaller cross-sectional area of the sensor. Also a smaller static force of 1 N was used.

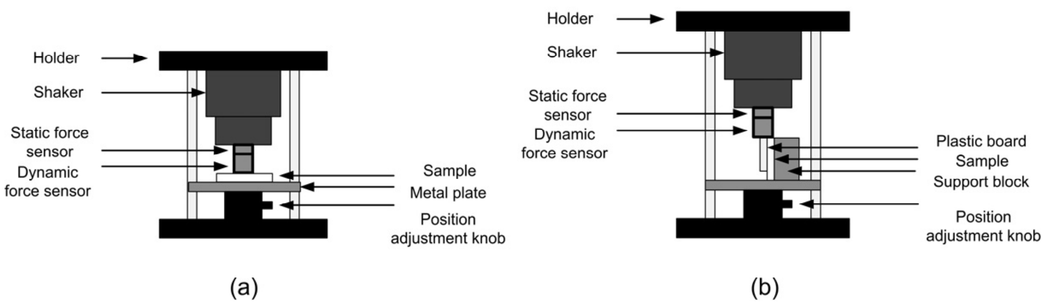

Fig. 1. Sensitivity measurement setup of (a) normal force (n = 3) and (b) shear forces related to the length (n = 1) and width (n = 2) of the sensor.

4. Results

The average force sensitivities computed from the calibration result of the PVDF material were (12.6 ± 0.8) mV/N for the normal force and (223.9 ± 20.3) mV/N and (55.2 ± 11.9) mV/N for the shear forces (n = 1 and n = 2, respectively). The average normal force sensitivity of the EMFi material was found to be (58.7 ± 16.5) mV/N. In shear force directions (n = 1 and n = 2), instead, the variation was too small and irregular to determine the sensitivity in these directions.

5. Discussion

The calibration of the PVDF sensor elements provided realistic results. The output voltage of a PVDF sensor element in a certain direction is dependent on the cross-sectional area of the sensor in that direction. Smaller cross-sectional area results in a sharp increase in output voltage [7]. The cross-sectional area of the sensor in the direction of mechanical axes n = 1 and n = 2 should be approximately the same and thus the sensitivities in these directions should have almost the same ratio as the piezoelectric coefficients d_{31} and d_{32} ($d_{32} = 0.1d_{31}$). This mainly occurred here. In the normal force direction the sensitivity is remarkably smaller due to the larger cross-sectional area.

The sensitivity of the EMFi sensor in the normal force direction was found to be approximately five-fold when compared to the corresponding value of the PVDF sensor. The higher sensitivity of the EMFi material is mainly due to the internal voided structure. However, due to the relatively large gas voids and local corona breakdowns, sensitivity varies in different parts of the film.

The advantage of the EMFi material over other polymer electrets is based on its flexibility due to the voided internal structure [11]. The base material of EMFi is inexpensive PP, which makes it applicable also for large area sensors like floor monitoring systems [11, 14]. Compared to the EMFi material, piezoelectric polymers usually contain fluoride which is a potentially toxic substance; this can be considered as a disadvantage [3, 14]. The main advantage of the PVDF material, however, is its sensitivity to forces related to its length and width. This property creates many versatile applications for the material, e.g. the material can be utilized also as a shear stress sensor, see reference [15].

References

[1] Vinogradov A. Piezoelectricity in Polymers. In: *Encyclopedia of Smart Materials*. New York: John Wiley & Sons, Inc., 2002.

[2] Harrison JS & Ounaies Z. Polymers, Piezoelectric. In: *Encyclopedia of Smart Materials*. New York: John Wiley & Sons, Inc., 2002.

[3] Paajanen M. The cellular polypropylene electret material – Electromechanical properties. Doctoral thesis, VTT Chemical Technology, 2001.

[4] Bauer S, Bauer-Gogonea S, Dansachmuller M, Graz I, Leonhartsberger H, Salhofer H & Schwodiauer R. Modern electrets. *IEEE Symp. Ultrasonics*, 2003, p. 370-376.

[5] Bauer S, Bauer-Gogonea S, Dansachmuller M, Hoislbauer H, Lindner M & Schwodiauer R. Physics of electromechanically active, cellular materials. *11th Int. Symp. Electrets*, 2002, p. 50-53.

[6] Eberle G, Schmidt H & Eisenmenger W. Piezoelectric polymer electrets. *IEEE Trans. Dielectr. Electr. Insul.*, 1996;**3**;624-46.

[7] Measurement Specialties Inc. Piezo film sensors. Available online at: http://www.meas-spec.com (accessed 28 May 2010).

[8] Kirjavainen K. Electromechanical Film and procedure for manufacturing same. U.S. Patent No. 4654546, 1987.

[9] Paajanen M, Välimäki H & Lekkala J. Modelling the electromechanical film (EMFi). *J. Electrostat.*, 2000;**48**;193-204.

[10] Lekkala J & Paajanen M. EMFi - New electret material for sensors and actuators. *10th Int. Symp. Electrets*, 1999, p. 743-746.

[11] Paajanen M, Lekkala J & Kirjavainen K. ElectroMechanical Film (EMFi) — a new multipurpose electret material. *Sens. Actuators A*, 2000;**84**;95-102.

[12] Emfit Ltd. Calculating the output voltage of Emfit sensors. Available online at: http://www.emfit.com (accessed 28 May 2010).

[13] Kärki S. Film-type sensor materials in measurement of physiological force and pressure variables. Doctoral thesis, Tampere University of Technology, 2009.

[14] Lekkala J, Tuppurainen J & Paajanen M. Material and operational properties of large-area membrane type sensors for smart environments. XVII IMEKO World Congress, 2003.

[15] Kärki S, Lekkala J, Kuokkanen H & Halttunen J. Development of a piezoelectric polymer film sensor for plantar normal and shear stress measurements. *Sens. Actuators A,* 2009;**154**;57-64.